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NETWORK APPLICATIONS OF THE USGS BRANCH MODEL

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ABSTRACT

Applications of a numerical model for simulating unsteady flow in dendritic or interconnected open-channel networks are presented to demonstrate the model's potential for addressing environmental problems and formulating engineering decisions in water-resources investigations. The model is computationally robust and readily adaptable to a broad spectrum of hydraulic conditions and open-channel configurations. The four-point, implicit, finite-difference model has been implemented on numerous open-channel reaches and networks in support of various water-resources investigations conducted within the U.S. Geological Survey. In this paper, network applications of the model to a residential canal system in Cape Coral, Florida; to a distributary system of channels in the Knik-Matanuska Rivers near Cook Inlet, Alaska; and to the tidal Potomac River and its tributaries near Washington, D.C., are described.

INTRODUCTION

Networks of open channels of varied geometric properties and diverse hydraulic conditions exist inland and along the coast. These channel networks are frequently manifested in dendritic and interconnected configurations in riverine deltas, estuarine wetlands, alluvial floodplains, and urban watersheds, as well as irrigation and residential-canal systems and navigational waterways. The importance of these networks spans the range of their disparate uses for drinking-water supply and effluent disposal to agricultural irrigation and life support for marine inhabitants. They typically are continually stressed systems that present unique and very difficult environmental problems and engineering questions for water-management officials.

Frequently, numerical modeling is the best approach for analyzing and understanding the hydrodynamic and transport mechanisms that govern the fate and distribution of solutes and contaminants in such environments. The expansive extents, irregular geometries, and dynamic interactions encountered in open-channel networks often dictate that numerical approximation of the governing equations in one space dimension may be the only computationally or economically feasible--i.e., practical--simulation approach.

Just as the importance of open-channel networks spans a number of disparate uses, their numerical simulation can involve a number of disparate difficulties, even within the context of a "simplified" numerical approach. Mixed regimes of gradually to rapidly varied flow can simultaneously prevail due to flash floods or flow regulations occurring in a single channel of the network.

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Local flows can vary from overbank-floodplain states to singularities produced by vanishingly small depths and even dry-channel conditions. Frequently, the effects of internal hydraulic structures within the domain of the open-channel network might also need to be accounted for and (or) investigated. Additionally, particular treatment may need to be given to nonuniform-flow distributions, nonlinear frictional effects, external inflows and outflows (including aquifer leakage), and the effects of meteorological forces.

In order to be useful for addressing environmental problems and engineering questions in varied open-channel networks, a numerical model must be computationally robust and readily adaptable to a broad spectrum of hydraulic and geometric conditions. The branch-network, dynamic-flow model, referred to as BRANCH, developed within the U.S. Geological Survey (USGS), designated as the USGS standard for unsteady open-channel-flow simulation, and documented in Schaffranek et al. (1981) possesses the attributes necessary to facilitate its implementation in a wide variety of open-channel networks. In this paper, the versatility of the BRANCH model is demonstrated by three applications which illustrate its utility in water-resources investigations. After some of the essential attributes of BRANCH are identified, brief descriptions of its applications to the Bluejay Canal system near Cape Coral, Florida; to the Knik-Matanuska Rivers and interconnecting channels near Cook Inlet, Alaska; and to the tidal Potomac River and tributaries near Washington, D.C., are presented. These and other applications of BRANCH described elsewhere (Holtschlag 1981, Jennings and Jeffcoat 1987, Schaffranek 1989, Stedfast 1981) present a variety of combined tidal and freshwater flows as well as complex cross-sectional geometries and channel configurations.

DESCRIPTION OF BRANCH MODEL

The unsteady, open-channel flow equations used in BRANCH account for nonuniform-flow distribution through the Boussinesq coefficient, accommodate channel storage and conveyance separation, allow for time-varying nodal and lateral flows, and include wind stress as a forcing function on the water surface (Schaffranek 1987a). A four-point, or box, finite-difference scheme is used to represent the equations, which are formulated with water-surface elevation and discharge as the dependent variables. The four-point scheme, with weighting factors for function values and their spatial derivatives, provides a high degree of flexibility for simulating diverse flow conditions in channels of variable geometric properties. Flow equations are transformed into equations relating unknowns at the end points of the open-channel branches comprising the network. This local elimination of internal computational nodes reduces the order of the coefficient matrices and, thereby, yields a significant savings in execution time and computer storage (Schaffranek et al. 1981). The matrix of branch-transformation equations, coupled with open-boundary and internal-junction equations, is solved by Gaussian elimination using maximum pivot strategy with optional iteration under user-specified tolerance controls.

The BRANCH model accepts cross-sectional geometries in which area, storage width, and conveyance width are specified as piece-wise linear functions of water-surface elevation. Observed, estimated, or previously computed initial values can be used to initiate the simulation, or the model can be "cold" started from hypothetical conditions. Boundary conditions, used to drive the model, can be specified by equations, functional relations, self-setting approximations, and (or) time-series input values. Frictional resistance can be related to hydraulic depth, water-surface elevation, flow discharge, water temperature, Froude number, or Reynolds number via an equation or set of tabular relations. The model includes a Lagrangian, particle-tracking algorithm for conservative solutes and a built-in interface for a transport model capable of treating reactive and nonconservative constituents.

BRANCH is coded in modular format using standard, transportable Fortran 77, making it compatible with mainframe, workstation, and PC systems. The model is supported by a project-level data-base system for pre-processing time-series, boundary-value data and for post-processing simulation results (Lai et al. 1978). An interface module facilitates the input of boundary-value data from, and output of simulation results to, the USGS National Water Information System (NWIS) data base. An interactive interface for Graphical Kernel System (GKS) libraries also accommodates customized display of model results on a wide variety of plotting devices.

BLUEJAY CANAL SYSTEM NEAR CAPE CORAL, FLORIDA

The Bluejay canal system is one of a number of tidally affected, manmade canal systems in Cape Coral, Florida, a residential development on the western side of the Florida peninsula. The canal system's only outlet is to the Caloosahatchee River near the river's mouth at San Carlos Bay in the Charlotte Harbor estuarine system. Canals in the Bluejay system range from 30 to 60 m in width and from 30 cm in depth at many of their ends to 9 m at locations near the Caloosahatchee River. The system also includes several large manmade lakes.

Oxygen deficits and anaerobic conditions can occur in the canal system because of the poor flushing capacity created by the enclosed nature of the canals and internal lakes. Additionally, the low tidal range--approximately 55 cm--at the Caloosahatchee River outlet, coupled with minimal freshwater inflows, except during storm events, hinders exchange of water between the canal system and the Gulf of Mexico. An adjacent canal system, the San Carlos, also has a single outlet to the Caloosahatchee River. Tides in the San Carlos system range about 37 cm and exhibit a 2-hour phase difference with tides in the Bluejay system. Typical maximum tidal-cycle discharges range from 30 m^3/s near the river outlet of the Bluejay system to 6 m^3/s in the interior of the San Carlos system.

A model of the combined Bluejay and San Carlos canal systems was developed to investigate the feasibility of exploiting the tidal-phase difference between the two systems in order to improve flushing (Goodwin 1991). The entire model of the 47-km length of canals consisted of 80 branches subdivided into 225 segments and connected at 73 junctions. Internal lakes in the system were schematized as open channels with an equivalent conveyance capacity. Boundary conditions used to drive the model were zero discharges at internal canal ends and recorded water-surface elevations at the outlets to the Caloosahatchee River. Recorded water-surface elevations and measured flow discharges at interior locations in the systems were used for calibration.

A tide-gate algorithm was incorporated (Schoellhamer 1988) and the model was used to evaluate the placement of a series of tide gates that would have the effect of enhancing ebb flow and, thereby, increasing flushing of both canal systems (Goodwin 1991). An objective function was defined to evaluate changes in flushing capacities for various gate sizes, combinations, and locations. Improved flushing of the large lakes was emphasized in developing the objective function and designing the tide gates. In the analysis, it was found that a single 3-meter-wide tide gate between the two canal systems could induce a mean discharge of 4.8 m^3/s, which would represent a volume of water equal to the total volume of the canals in about 15 days. Four tides gates induced a discharge of 7.9 m^3/s, representing a volume of water equal to the total canal volume in about 9 days. A video animation showing the effects of tide gates on flushing was subsequently produced from the model results (Schoellhamer 1988).

KNIK-MATANUSKA RIVER SYSTEM NEAR COOK INLET, ALASKA

The Knik and Matanuska Rivers originate at large glaciers in the Chugach Mountains and connect with Knik Arm of Cook Inlet about 64 km northeast of Anchorage, Alaska. Increased development produced serious traffic problems along Glenn Highway, which crosses the rivers in an intertidal marsh at roughly the transition between the tidal-affected rivers and the Knik Arm estuary. In an effort to reduce congestion, construction of additional bridges at the Glenn Highway crossing was planned. In 1984, a study of the flow characteristics of the rivers near Glenn Highway was undertaken for use in designing the proposed bridge-span openings (Lipscomb 1989).

Flow in the complex system of interconnected channels in the 3.2-km-wide tidal floodplain of the Knik-Matanuska Rivers is compounded by semi-diurnal tides propagating up Knik Arm and glacial breakout floods traveling downstream. The tidal range in Cook Inlet is among the largest in the world, decreasing from 10.7 m at Anchorage to 3 m at the Glenn Highway crossing. The Knik River has an average flow of about 198 m^3/s at the upstream end of the 11.7-km study reach and a fall of about 5 m through the reach. Flow in the Matanuska River averages 113 m^3/s at the upstream end of the 17.7-km study reach and has a fall that exceeds 45 m. During glacial-breakout years, maximum discharges can exceed those of nonbreakout years by an order of magnitude.

The original BRANCH model layout of the Knik-Matanuska network consisted of 6 open-boundary junctions, 19 internal junctions, and 33 channel branches (Lipscomb 1989). For purposes of analyzing the flow distribution in the vicinity of the proposed new bridge-span openings, the model was subsequently extended, and recorded tidal elevations were used to drive the model at a single, downstream open boundary located within Knik Arm. Of particular difficulty in the implementation of the model were changes in the configuration of the channels immediately upstream from the highway at various flow rates. A tabular frictional-resistance capability was added to the model (Schaffranek 1987a) to accommodate the potential drying of channels at low flows without having to restructure the coefficient matrices during the course of the simulation. This capability facilitated the synthesis of potentially drying channels as having artificially deepened sections with high frictional resistance to minimize conveyance at low discharges (Lipscomb 1989).

The model was calibrated and verified using sets of measured tidal-cycle discharges. The calibrated model was then used to quantify the flow distributions for design flood conditions and six different bridge-opening configurations (Lipscomb 1989). The model indicated that substantial changes in circulation patterns and flow distributions would occur in the channels immediately upstream from the highway crossing as a result of combined backwater effects and tidal forcing for various bridge-opening designs. The simulated flow distributions and resultant circulation patterns in the vicinity of the highway crossing were used to guide the design of the proposed new bridges.

TIDAL POTOMAC RIVER NEAR WASHINGTON, D.C.

The tidal river segment of the Potomac River extends downstream from the head-of-tide, near Chain Bridge in the northwest quadrant of the District of

Columbia, a distance of nearly 50 km to Indian Head, Maryland. The Anacostia River, Roosevelt Island Channel, Washington Channel, Washington Tidal Basin, and the tidal inlets of Broad Creek, Piscataway Creek, Dogue Creek, Gunston Cove, Pohick Bay, and Accotink Bay form the tidal Potomac River network. The cross-sectional area of the tidal river expands over fortyfold between Chain Bridge and Indian Head, increasing from 232 to 9,960 m^2. The corresponding width increases from 44 to 1,950 m. Although the channel bottom is somewhat irregular, in general, depths range from about 9 m at Chain Bridge to 12 m at Indian Head. Depths in the tributaries and tidal inlets are typically 3 m or less. Imbalances in the riverine ecosystems of the tidal Potomac River have led to algal blooms, low dissolved-oxygen concentrations, and changes in marine inhabitants and aquatic vegetation (Callender et al. 1984).

A model consisting of 25 branches joining or terminating at 25 nodes was developed (Schaffranek 1982) in order to study the flow dynamics of the tidal-river system. A total of 66 cross sections located at intervals ranging from 0.7 to 4.8 km was used to depict the irregular geometry of the tidal river and its tributaries and tidal inlets. Boundary conditions used to implement the model were zero discharges at the ends of tributaries and inlets, tidal elevations recorded at Indian Head, and freshwater inflows derived from a rated gaging station near the head-of-tide. The model was calibrated and verified using measured tidal-cycle discharges. Measured and model-computed flood and ebb flow volumes were within 10 percent (Schaffranek 1987b).

The model was used to evaluate the flushing capacity and retention properties of the tidal-river system for analyzing factors contributing to the development of algal blooms and the fate of phytoplankton. A Lagrangian particle-tracking scheme was incorporated to examine the retention times for parcels of water (Schaffranek 1982). Retention times were found to vary considerably in response to changes in freshwater inflows, tidal dynamics, and meteorological conditions. Freshwater inflows to the tidal Potomac River average 323 m^3/s but have ranged from 3 to 13,700 m^3/s. Tidal amplitude at Indian Head is about 55 cm, but wind effects can significantly dampen tidal propagation. Use of the model made it possible to identify local flow patterns under various combinations of boundary conditions and to investigate the role of tidal trapping in the fate of phytoplankton. Retention times in the main Potomac River channel were found to be weeks to months for low to moderate inflows, but only several days for high inflows from upstream storms. Retention times in the tributary channels and inlets were found to be greater that those of the main channel and more affected by local drainage-basin storm events.

SUMMARY

Applications of the USGS branch-network dynamic-flow model have demonstrated its potential for addressing environmental problems and formulating engineering decisions in complex networks of open channels. The model is a powerful alternative to steady-state methods of analysis that have previously been employed in open-channel networks considered too complicated to be amenable to investigation by unsteady-flow simulation techniques. The flexibility and adaptability of the model are illustrated by its use to investigate degrading water-quality conditions in a residential canal system in Cape Coral, Florida; to study the effects of bridge-design alternatives in a system of channels in the alluvial floodplain of the Knik-Matanuska Rivers near Cook Inlet, Alaska; and to analyze flushing dynamics of the main channel and tributaries of the tidal Potomac River near Washington, D.C.

REFERENCES

Callender, E., Carter, V., Hahl, D.C., Hitt, K. and Schultz, B.I. (1984). "A water-quality study of the tidal Potomac River and Estuary--an overview." Water-Supply Paper 2233, U.S. Geological Survey, 46 p.

Goodwin, C.R. (1991). "Simulation of the effects of proposed tide gates on circulation, flushing, and water quality in residential canals, Cape Coral, Florida." Open File Report 91-237, U.S. Geological Survey, 43 p.

Holtschlag, D.J. (1981). "Flow model of the Saginaw River near Saginaw, Michigan." Open-File Report 81-1061, U.S. Geological Survey, 20 p.

Jennings, M.E., and Jeffcoat, H.H. (1987). "Computation of unsteady flows in the Alabama River." *Water Resources Bulletin*, 23(2), 313-315.

Lai, Chintu, Schaffranek, R.W., and Baltzer, R.A. (1978). "An operational system for implementing simulation models, a case study." *Specialty Conference on Verification of Mathematical and Physical Models in Hydraulic Engineering*, ASCE, New York, N.Y., pp. 415-454.

Lipscomb, S.W. (1989). "Flow and hydraulic characteristics of the Knik-Matanuska River estuary, Cook Inlet, southcentral Alaska." Water-Resources Investigations Report 89-4064, U.S. Geological Survey, 52 p.

Schaffranek, R.W. (1982). "A flow model for assessing the tidal Potomac River." *Specialty Conference on Applying Research to Hydraulic Practice*, ASCE, New York, N.Y., pp. 531-545.

Schaffranek, R.W. (1987a). "Flow model for open-channel reach or network." Professional Paper 1384, U.S. Geological Survey, 11 p.

Schaffranek, R.W. (1987b). "A flow-simulation model of the tidal Potomac River." Water-Supply Paper 2234-D, U.S. Geological Survey, 41 p.

Schaffranek, R.W. (1989). "Proceedings of the advanced seminar on one-dimensional, open-channel flow and transport modeling." Water-Resources Investigations Report 89-4061, U.S. Geological Survey, 99 p.

Schaffranek, R.W., Baltzer, R.A., and Goldberg, D.E. (1981). "A model for simulation of flow in singular and interconnected channels." Techniques of Water-Resources Investigations Report, book 7, chap. C3, U.S. Geological Survey, 110 p.

Schoellhamer, D.H. (1988). "Simulation and video animation of canal flushing created by a tide gate." *1988 National Conference on Hydraulic Engineering*, ASCE, New York, N.Y., pp. 788-793.

Stedfast, D.A. (1981). "Flow model of the Hudson River estuary from Albany to New Hamburg, New York." Water-Resources Investigations Report 81-55, U.S. Geological Survey, 76 p.